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# Implications of Early Cenozoic uplift and fault reactivation for carbon storage in the Moray Firth Basin

Gustavo J. Guariguata-Rojas<sup>1</sup> and John R. Underhill<sup>1</sup>

## Abstract

Interpretation and depth conversion of an extensive, well-calibrated seismic database provide the basis upon which to map the limits and evaluate the geologic risks of using a saline aquifer target for carbon dioxide (CO<sub>2</sub>) storage in the Moray Firth Basin of the North Sea. The seismic interpretation demonstrates that the Lower Cretaceous (Albian-Aptian) Captain Sandstone Member is a continuous, interconnected reservoir that rises to subcrop in the western areas of the basin as a consequence of Early Cenozoic uplift and tilt. As such, the aquifer forms an open system with few barriers or sizable closures to arrest or entrap light fluids and gases en route to its western subcrop. The new interpretation also indicates that the saline aquifer is cut by several west-southwest/east-northeast-striking reactivated normal faults. Although migration along the faults permitted hydrocarbons to get into structurally elevated traps, such as the Captain Field itself, some faults also breach the seal of the Captain Sandstone Member aquifer, rise to the seabed, and increase the risk of seabed leakage. Consequently, despite its large storage capacity, the dip, subcrop, and fault reactivation affecting the Captain Sandstone Member aquifer all suggest that its use as a site for CO<sub>2</sub> storage remains unproven and is not the best choice for an initial North Sea exemplar. As such, the study highlights the importance of undertaking a robust and forensic geologic screening of any prospective storage site prior to injection.

## Introduction

Many geoscientists consider that the geologic storage of carbon dioxide (CO<sub>2</sub>) offers a significant opportunity to arrest greenhouse gas emissions into the atmosphere and reduce our carbon footprint. For that potential to become a reality, it is a prerequisite to demonstrate that CO<sub>2</sub> can be safely stored and will not leak to the surface (Gunter et al., 2004; Pickup et al., 2011).

To date, CO<sub>2</sub> storage studies have primarily focused upon the use of subsurface reservoirs in depleted oil and gas fields or regionally extensive saline aquifers. Given the perceived scale of the challenge and amount of CO<sub>2</sub> that needs to be sequestered to stabilize or reverse emission levels, the geologic focus has largely been on regional saline aquifers because of their large lateral continuity, gross rock volume, and storage capacity (Gunter et al., 2004; Chadwick et al., 2008, 2009; Senior et al., 2010; Williams et al., 2014).

For any CO<sub>2</sub> storage option to be a success, there has to be a judicious choice of site predicated on a full assessment of its geologic suitability integrating all the available subsurface (seismic and well) data. If the wrong site is chosen as an exemplar and leakage occurs, the general case for CO<sub>2</sub> storage will be weakened and potentially undermined. Consequently, it is essen-

tial to obtain a high degree of confidence in the storage integrity of saline formations through a thorough understanding of the factors that govern the extent of the aquifer, its migration pathways, and their risk of leakage before injection is attempted (Gunter et al., 2004; Lewicki et al., 2006; Underhill et al., 2009; Senior et al., 2010; Yielding et al., 2011).

The North Sea remains a frontier for CO<sub>2</sub> storage. However, its petroleum exploration and development history has led to the compilation of an extensive data and knowledge base upon which to assess its potential for CO<sub>2</sub> storage in depleted oil and gas field reservoirs and saline aquifers. One North Sea reservoir that has received particular attention is the Lower Cretaceous Captain Sandstone Member in the Moray Firth Basin, primarily because of its areal extent and large storage capacity (Quinn et al., 2010; Jin et al., 2012; Hangx et al., 2013; Williams et al., 2016). Some estimates suggest that it could store 358 million tons of CO<sub>2</sub>, if its boundaries were closed to flow, and up to 1668 million tons if it acted as an open system (Jin et al., 2012; Jin et al., 2012).

Although its extent and capacity make the Captain Sandstone Member saline aquifer appear to be a good candidate for CO<sub>2</sub> injection, it remains essential to

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investigate and understand the critical factors that ultimately govern its viability as a geologic repository for CO<sub>2</sub> storage. The main aim of this paper is to show how the interpretation of an extensive subsurface database, consisting of 2D and 3D seismic data calibrated by exploration wells and the maps that result there from, provide the basis upon which to assess the critical controls on the distribution of the Captain Sandstone Member and provide a geologic screening of its storage potential. The interpretations allow us to confidently define the areal extent of the Captain Sandstone Member saline aquifer target and an evaluation of the nature and role of the faulting that affects it. Instead of supporting the case for using the Captain Sandstone Member saline aquifer as a CO<sub>2</sub> injection site, the new mapping suggests that there is a need to be cautious about its suitability for storage, especially in the western areas of the basin because the aquifer is continuous, rises to subcrop at the seabed and is transected by reactivated faults.

## Geologic setting

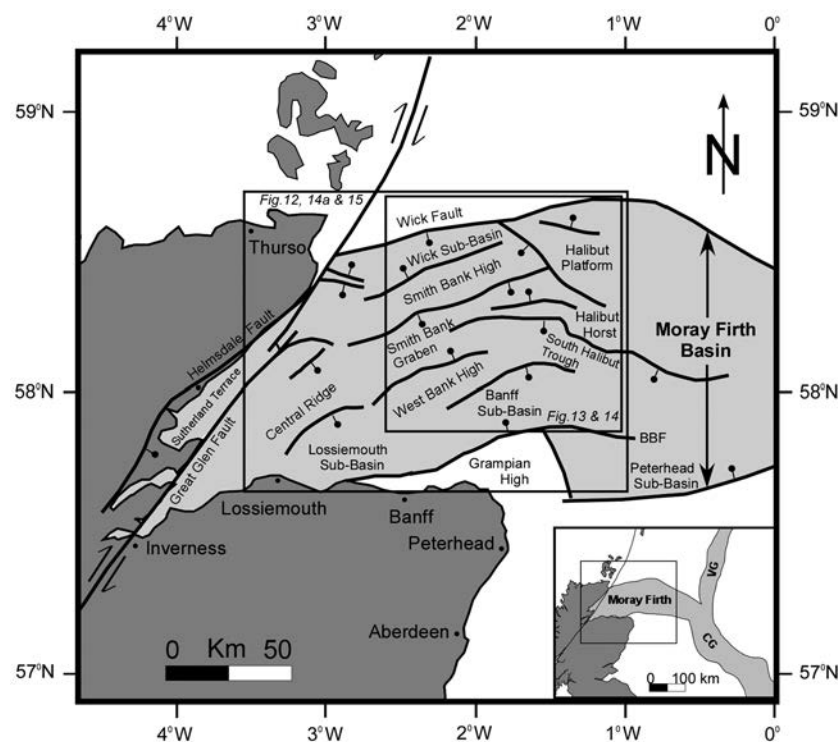
### *Tectonic and stratigraphic evolution of the Moray Firth*

The Moray Firth (MF) Basin represents the western arm of the North Sea trilete rift system (Figure 1). Its stratigraphic development and evolution primarily reflects Upper Jurassic extensional activity characterized

by the occurrence of numerous fault-bound (synrift) half-graben depocenters followed by passive (Cretaceous to recent) postrift infill (Figure 2; Underhill, 1991; Pinnock and Clitheroe, 1997; Glennie and Underhill, 1998; Argent et al., 2000; Rose et al., 2000). The basin's early postrift deposition is represented by the (Lower Cretaceous) Cromer Knoll Group, a clastic succession that includes regionally extensive sandstones ascribed to the Wick Sandstone Formation (Johnson and Lott, 1993). Conformance with the buried synrift depocenters, particularly those on the southern side of the Halibut Horst, suggests that the extensional subbasins continued to influence basin bathymetry in the Lower Cretaceous through compaction or via limited and localized fault activity (Wilson et al., 2005).

Toward the end of the Early Cretaceous, clastic sedimentation was succeeded by carbonate deposition marked by the (Upper Cretaceous) Chalk Group (Figure 2), something that reflects deposition in clean, well-aerated waters at a time of eustatic highstand. A return to clastic deposition in Early Cenozoic times occurred in response to tectonic uplift and shallowing associated with the development of the proto-Iceland plume on the Atlantic Margin (Glennie and Underhill, 1998; Mackay et al., 2005), an event that punctuated the general pattern of postrift thermal subsidence. As a result of the uplift, progressively older strata subcrop westward (Argent et al., 2000, 2002) leading to Jurassic strata subcrop in the Sutherland Terrace and exposed along the Sutherland Coast (Underhill, 1991). The Early Cenozoic deformation also provided the driver for easterly directed progradation and rotation of Paleogene deltaic sediments (Milton et al., 1990; Thomson and Underhill, 1993; Hillis et al., 1994; Hillis, 1995; Thomson and Hillis, 1995), during a phase of tectonically induced forced regression (Underhill, 2001).

The Early Cenozoic uplift led to the rejuvenation of precursor Upper Jurassic synrift normal faults (Argent et al., 2002), the formation of new extensional structures and the dextral reactivation of the Great Glen Fault (Underhill, 1991; Thomson and Underhill, 1993; Underhill and Brodie, 1993), all of which had a profound impact on petroleum prospectivity. Despite considerable exploration activity in the basin, the Inner MF has proved to be less prospective than other parts of the North Sea (David, 1996). With the notable exception of the Beatrice Field (Linsley et al., 1980; Peters et al. 1989; Stevens, 1991), exploration for extensional fault blocks containing Lower and Middle Jurassic (prerift) reservoirs has proven to be particularly disappointing in western areas, primarily



**Figure 1.** Location map showing the main structural elements of the MF Basin and its position relative to the North Sea's trilete rift system (lower right inset). The rectangular boxed areas equates with the areal extent of top structure maps displayed in the paper (Figures 12–15; Bosies Bank Fault [BBF], Central Graben [CG], and Viking Graben [VG]).



because reactivated faults breach, limit the size of traps, and rise to the seabed. Where the faults propagated up into the Mesozoic section, they acted as migration pathways to charge Lower Cretaceous clastic reservoirs (e.g., at the Captain Field; Pinnock and Clitheroe, 1997; Rose, 1999; Rose et al., 2000). However, even where that occurred, traps were prone to biodegradation due to their shallow burial resulting from the Early Cenozoic uplift. The clear implication is that faults are a major control on prospectivity, promoting fluid migration to higher stratigraphic levels, which in some places led to fluid escape and leakage at the seabed.

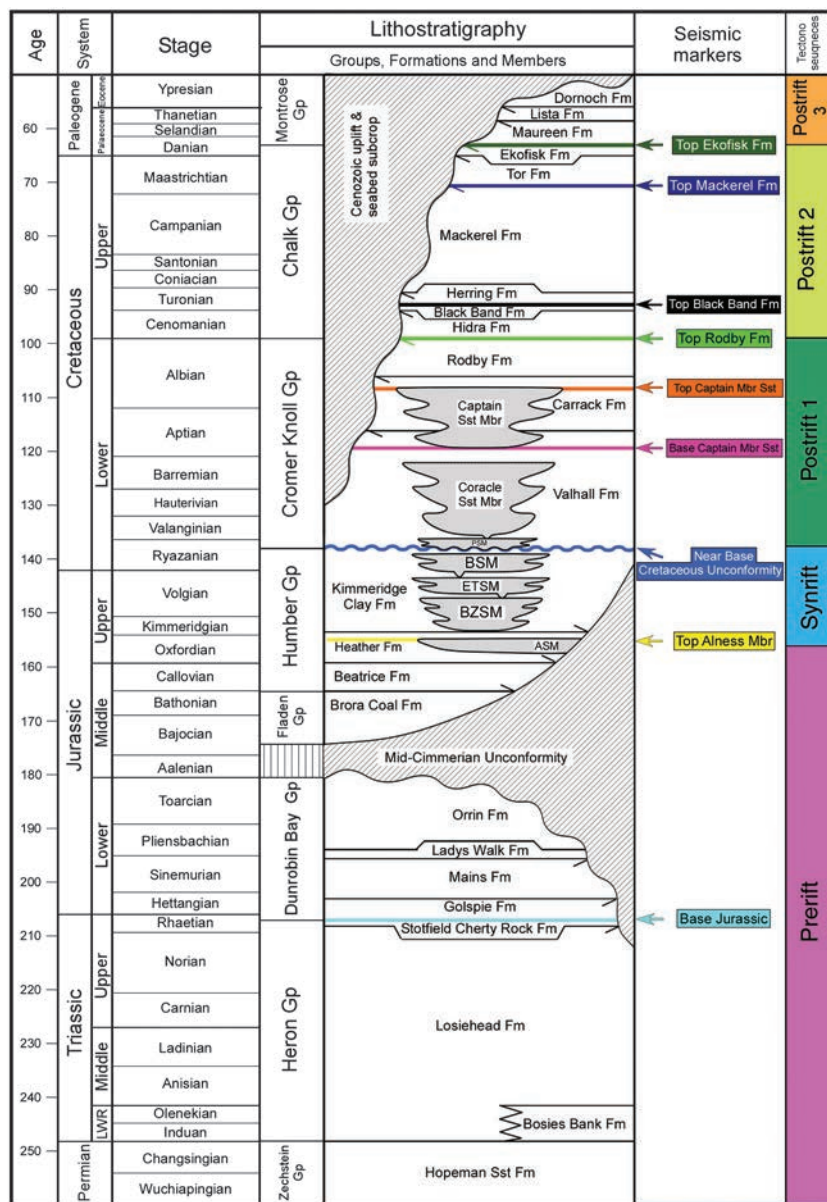
### The Captain Sandstone Member Stratigraphy

The Captain Sandstone Member represents the youngest subdivision of Lower Cretaceous (Albian-Aptian) Wick Sandstone Formation of the Cromer Knoll Group (Figure 2; Johnson and Lott, 1993; Crittenden et al., 1997, 1998; Argent et al., 2000). The two, older, sand-prone subdivisions of the Wick Sandstone Formation are the Ryazanian-Valanginian, Punt Sandstone Member, and the Hauterivian-Barremian, Coracle Sandstone Member. In some publications, the Punt, Coracle, and Captain sandstones have also been informally referred to as the Wick A, Wick B, and Wick C Members, respectively (Argent et al., 2000; Copestake et al., 2003).

Integration of biostratigraphy and seismic interpretation during exploration and appraisal activities subsequently enabled component parts of the Cromer Knoll Group to be placed in a sequence stratigraphic framework consisting of eight genetic stratigraphic (K-) sequences defined by regionally extensive maximum flooding surfaces and marine condensed horizons (Copestake et al., 2003). The Captain Sandstone Member lies within Copestake et al. (2003) K45 sequence and Jeremiah's (2000) K-80 and K-85 sequences. Biostratigraphic evidence either places it in the LK8 (in part) and LK9 palynological zones and *nutfieldensis* to *tardefucata* ammonite zones of Upper Aptian-Lower Albian age (Jeremiah, 2000) or the (younger) *forbesi* ammonite zone. Either way, the Captain Sandstone Member is readily identifiable on seismic and well-log data, something that provides an excellent basis for mapping its distribution in the basin.

Regional mapping demonstrates that the Captain Sandstone Member clastic system extends over a distance of almost

200 km (Argent et al., 2000; Jeremiah, 2000; Wilson et al., 2005). The depositional system was initially called the "Captain-Glenn" or "Kopervik" play fairway by Wilson et al. (2005). Exploration of the Lower Cretaceous targets along the length of the play fairway initially led to the discovery of the Captain Field in 1977 and subsequent Atlantic, Blake, Cromarty, Hannay, Glenn West, Glenn East, and Goldeneye Fields of United Kingdom Continental Shelf (UKCS) quadrants 13, 14, 20, and 21 (Figure 3; David, 1996; Du et al., 2000; Garrett et al., 2000; Jeremiah, 2000; Law et al., 2000; Copestake et al., 2003; Argent et al., 2005; Wilson et al., 2005).



**Figure 2.** Stratigraphy of the MF Basin. The figure relates the main lithostratigraphic units to their respective tectonostratigraphic sequences and also highlights the occurrence of the main unconformities and seismic horizons mapped in the study (Alness Spiculite Member [ASM], Burns Sandstone Member [BSM], Buzzard Sandstone Member [BZSM], Ettrick Sandstone Member [ETSM], and Punt Sandstone Member [PSM]).

A similar, but less-confined Britannia Sandstone Member play fairway occurs to the northeast of the Halibut Horst (Figure 1), in UKCS quadrants 15 and 16. The Britannia Sandstone Member consists of a distributary channel complex and effectively represents a northerly counterpart to the Captain Sandstone Member in the Witch Ground Graben (Bisewski, 1990; Wilson et al., 2005), where it forms the main reservoir in the Britannia Field itself. The Captain and Britannia Sandstone Members lie encased in shales ascribed to the Valhall and Carrack Formations (Jeremiah, 2000), and they are regionally sealed by smectite-rich shales belonging to the Carrack Formation itself or by the overlying calcareous shales of the (Upper Albian) Rødby Formation.

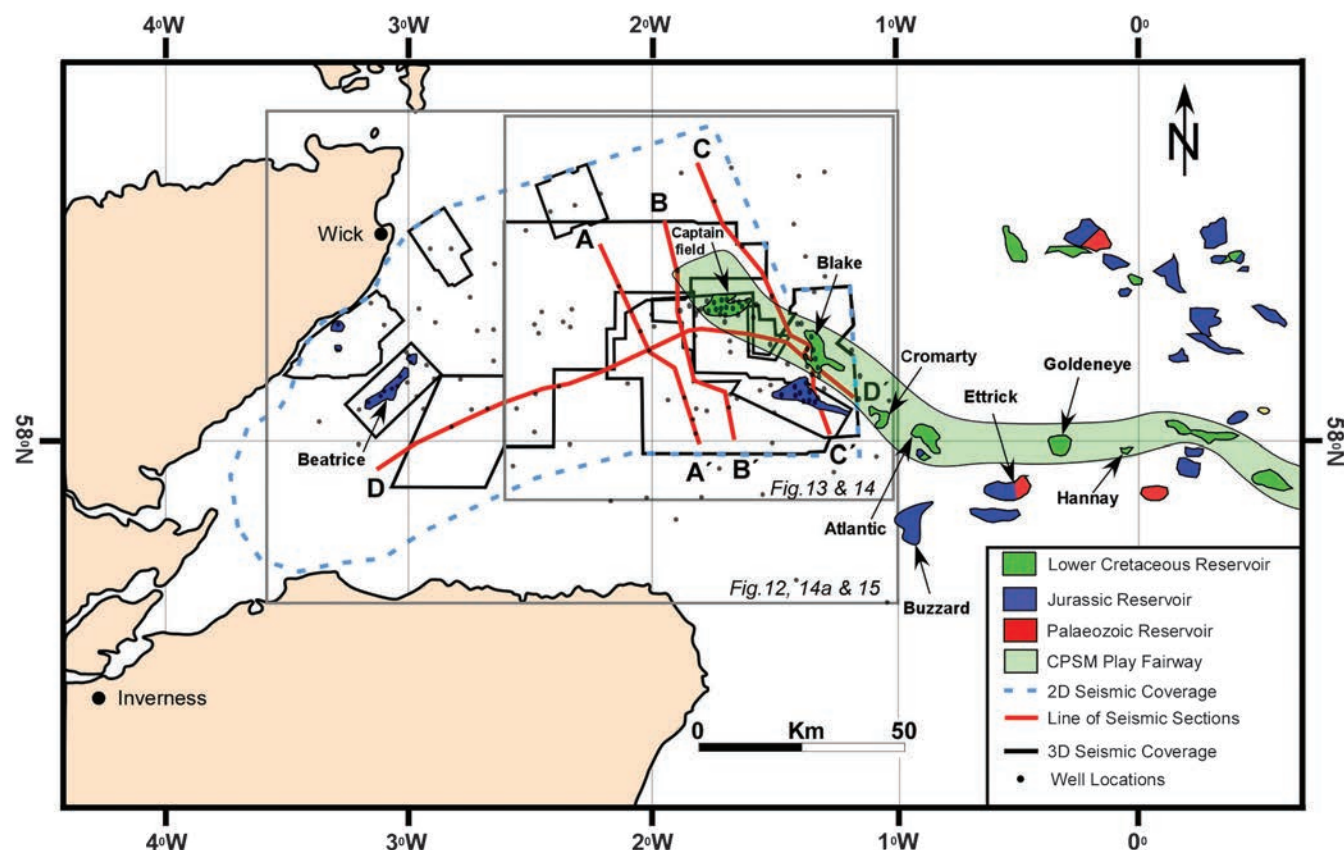
Regional and local correlations show that the Captain Sandstone Member itself may be subdivided into two component parts, informally known as the Upper and Lower Captain Sandstones, which are separated by the regionally correlatable Mid Captain Shale (Rose, 1999; Jeremiah, 2000; Rose et al., 2000). Both sandstone subunits have strongly erosive bases that are generally interpreted as sequence boundaries. In the case of the Upper Captain Sandstone, this may indicate that the Mid Captain Shale is cut-out by incision and is locally discontinuous (Jin et al., 2012). Erosional down-cut by the Lower Captain Sandstone has also locally re-

moved a significant part of the underlying section (e.g., in the Goldeneye Field; Marshall et al., 2016).

#### Reservoir properties

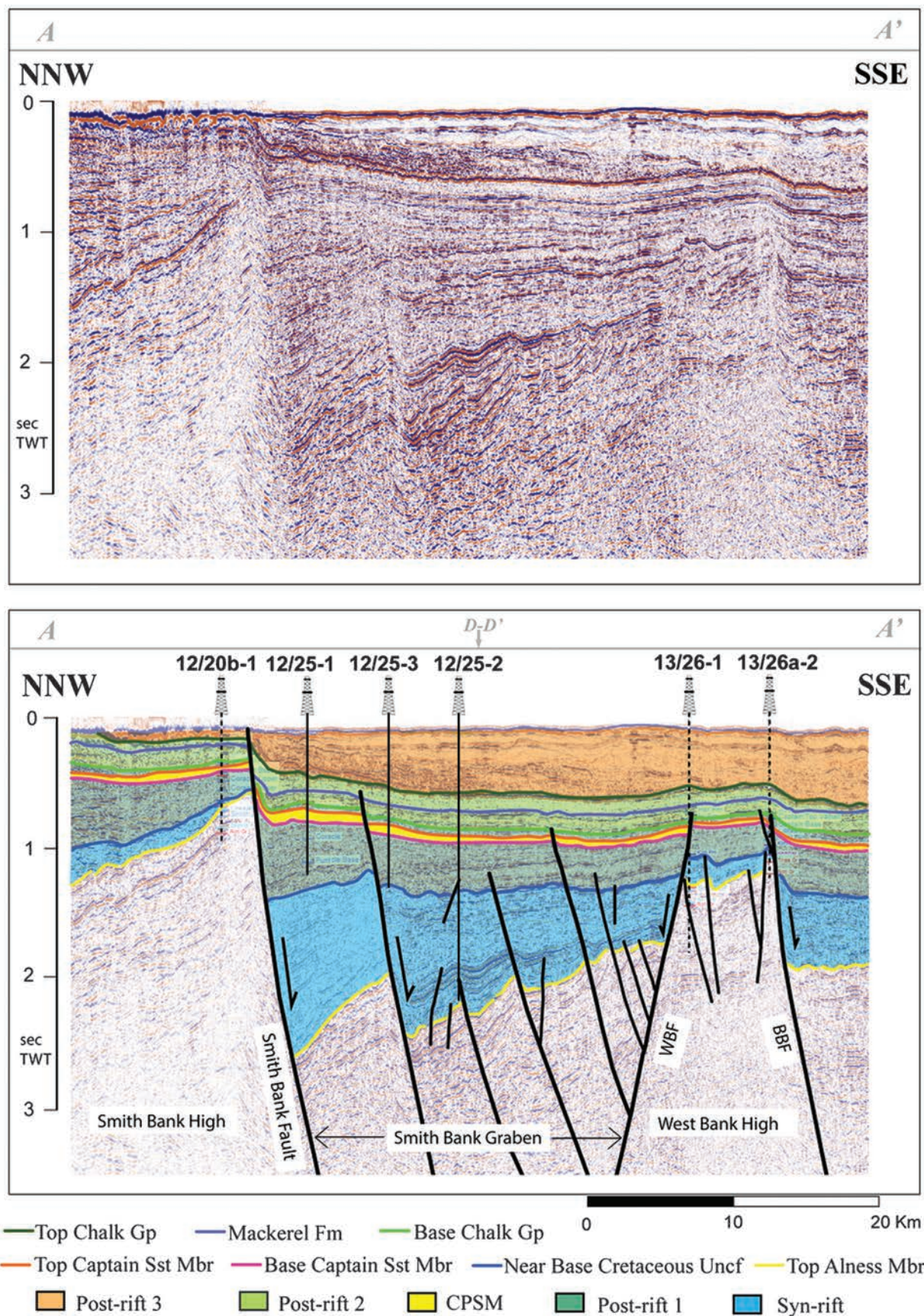
The Captain Sandstone Member comprises thick-bedded, stacked, marine, deep-water mass flow deposits (Pinnock and Clitheroe, 1997; Rose, 1999; Rose et al., 2000). The Captain Sandstone reservoir attains thicknesses in excess of 100 m in the northern Wick subbasin and in the hanging-wall depocenters of the South Halibut Trough (Rose, 1999; Pinnock et al., 2003), whereas thicknesses in the range of 60–100 m occur in elevated footwall locations along the Captain Ridge (e.g., at Blake; Du et al., 2000). The Captain Sandstone Member is also characterized by a high net-to-gross ratios that commonly exceed 70% and range up to 98% locally (e.g., in Blake Field; Du et al., 2000).

The source of the sedimentary input to the basin has proved somewhat contentious. Although original depositional models emphasized coarse clastic input from northerly point sources (e.g., Law et al., 2000), other authors suggest that it represents a confined, axial, westerly sourced, high-density turbiditic system deposited along an elongate, 10–20 km wide channel complex located to the south of the Halibut Horst (Wilson et al., 2005). Individual channel systems have been reported



**Figure 3.** Location map of the MF area showing the well and seismic database used in the study. Major oil fields, gas fields, and the Cretaceous Play Fairway are all highlighted, including the Captain Field after which the Captain Sandstone Member is named. The rectangular gray boxes correspond to the areal extent of the top structure maps displayed in the paper (Figures 12–15).





**Figure 4.** Westernmost north-northwest/south-southeast-striking seismic line (A-A') demonstrating the reactivation of the Smith Bank Fault, which displaces all of the present stratigraphy and subcrops at the seabed (West Bank Fault [WBF] and Bosies Bank Fault [BBF]).



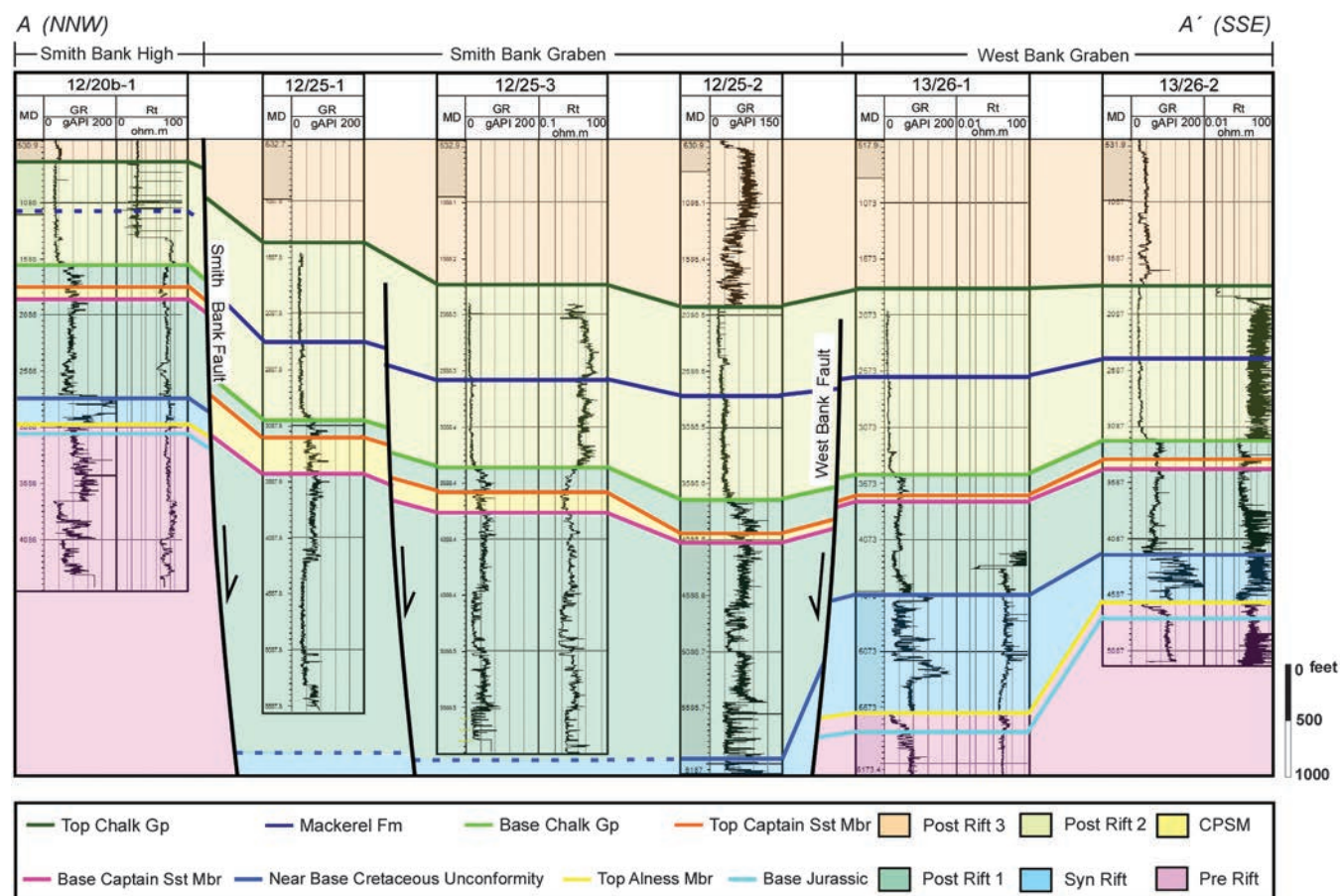
to reach widths of 1.5 km in the Blake Field, where they are bordered by, and encased within, overbank facies (Du et al., 2000), providing additional thin-bed pay.

Sandstones of the Captain Sandstone Member exhibit porosities of 25%–30% and permeabilities of several darcies (D). The Captain Field (Figure 3) has an average permeability of seven dimensions (Pinnock and Clitheroe, 1997; Rose, 1999; Rose et al., 2000; Hampson et al., 2010), whereas values of one and half dimensions to two dimensions are found in the Blake Field (Du et al., 2000). As Rose (1999) demonstrates, it is the combination of reservoir predictability, coarse grain size, high horizontal and vertical permeability, good connectivity, and its continuity that make it possible to produce heavy (18° API) and viscous oil from the Captain Sandstone Member in the Captain Field. Hydrostatic pressures measured from wells in the Captain Sandstone Member provide strong evidence that communication exists between fields throughout the whole play fairway, which suggests that there is good lateral sandstone continuity and a lack of compartmentalization.

As a result of their excellent reservoir properties, lateral continuity and high connectivity, the Captain and

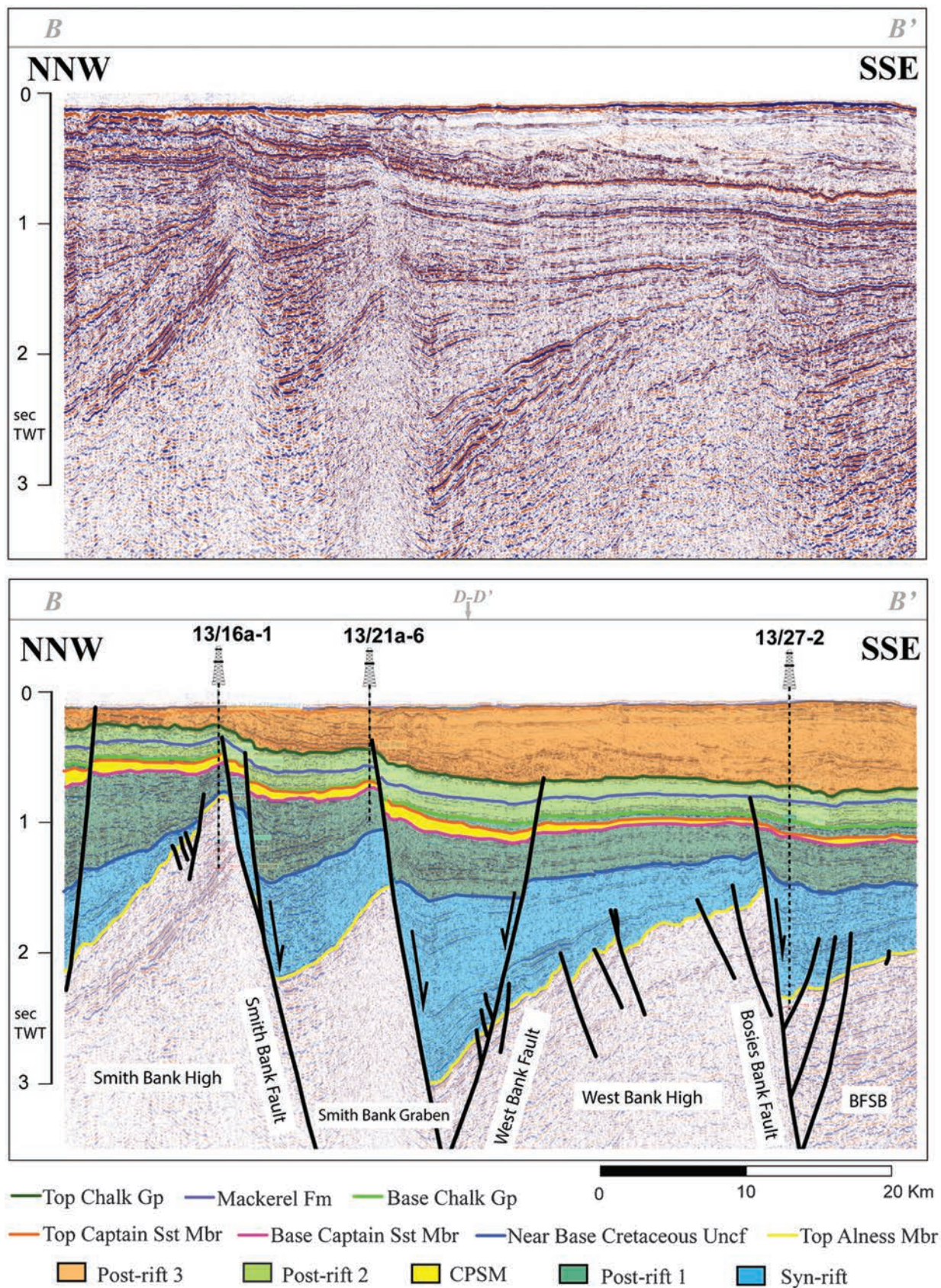
Britannia Sandstone Member systems have proved to be highly efficient carrier beds through which petroleum can, and has migrated. Thus, the Captain Sandstone Member may be considered a regional, homogeneous reservoir system. In the South Halibut Basin area, long-distance, lateral migration through the Captain aquifer has been demonstrated by both the occurrence of commercial quantities of gas condensate in the easterly Goldeneye Field, which is sourced from a kitchen more than 35 km to the east, and by a systematic reduction in oil API toward the shallower, western part of the play fairway (Wilson et al., 2005). In addition to demonstrating long-distance lateral migration, the decrease in viscosity is also consistent with biodegradation resulting from shallower burial depths and mixing from an open system to the west.

Petrographic studies have shown that the Captain Sandstone Member reservoir consists mainly of very fine to medium-grained quartz arenitic to subarkosic sandstones. The Upper Captain Sandstone Member has a higher lithic component, and it is slightly coarser grained than the Lower Captain Sandstone Member, and it is often referred to as being subarkosic (Pinnock and Clitheroe, 1997). The detrital components of the



**Figure 5.** Westernmost north-northwest/south-southeast-striking well-log correlation panel corresponding to the seismic line used in Figure 4 highlighting the effect that syn- and postdepositional faulting had on the thickness distribution of the Cromer Knoll Group in general and the Captain Sandstone Member in particular.



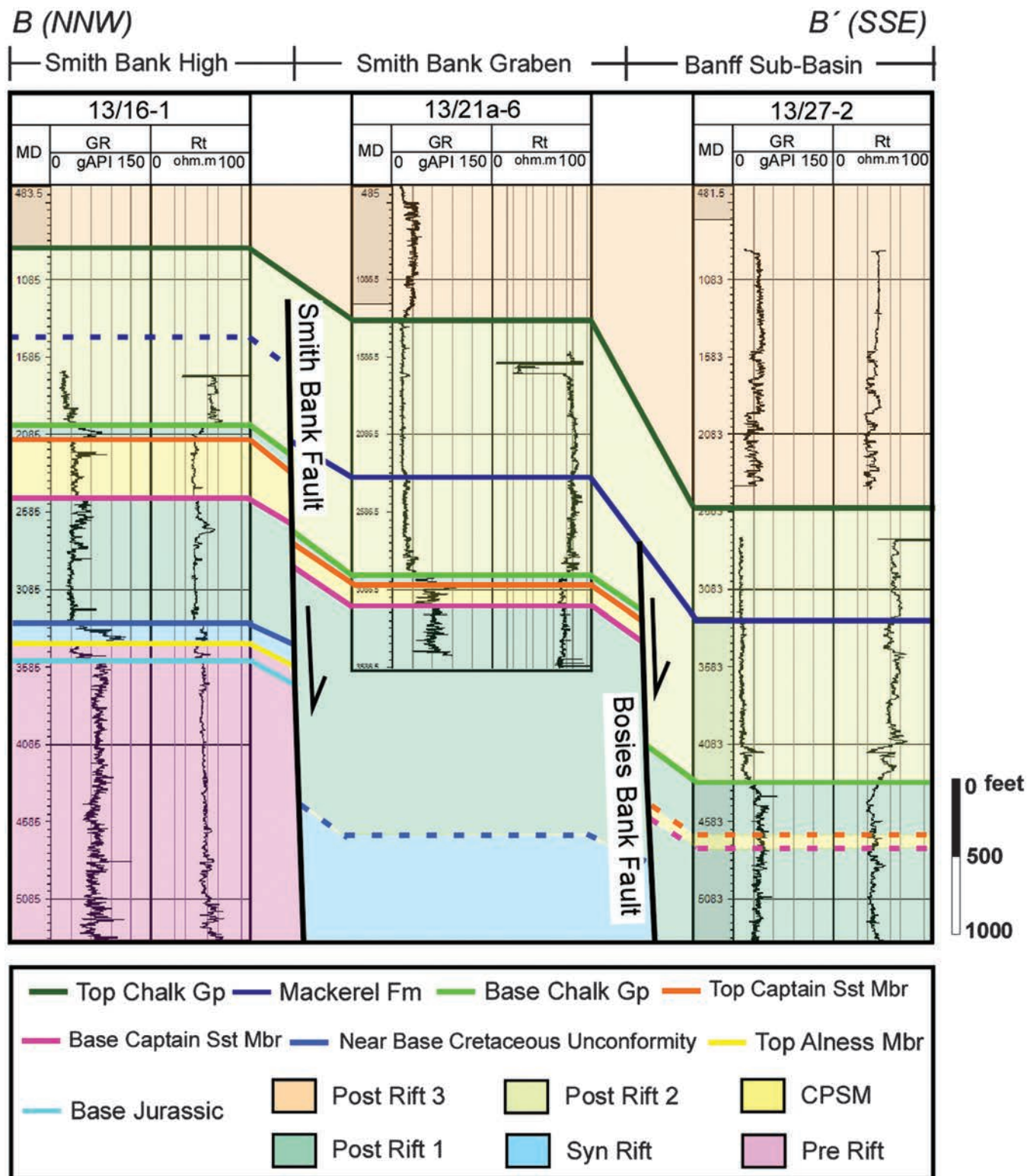


**Figure 6.** Central north-northwest/south-southeast-striking seismic line (B-B') across the Smith Bank High, West Bank High, and Banff Subbasin, demonstrating the reactivation of precursor normal faults. Significant faulting cuts through the Captain Sandstone Member and partially propagates into the overlying Tertiary clastics (Banff Subbasin [BFSB]).



Captain Sandstone Member are dominated by mono-crystalline and polycrystalline quartz with relatively small amounts of K-feldspar and lithic fragments (Pin-nock and Clitheroe, 1997).

The results of exploration in the Captain Sandstone Member play fairways of the basin therefore demonstrate that the reservoir has excellent reservoir properties and forms a highly efficient aquifer and a prospective

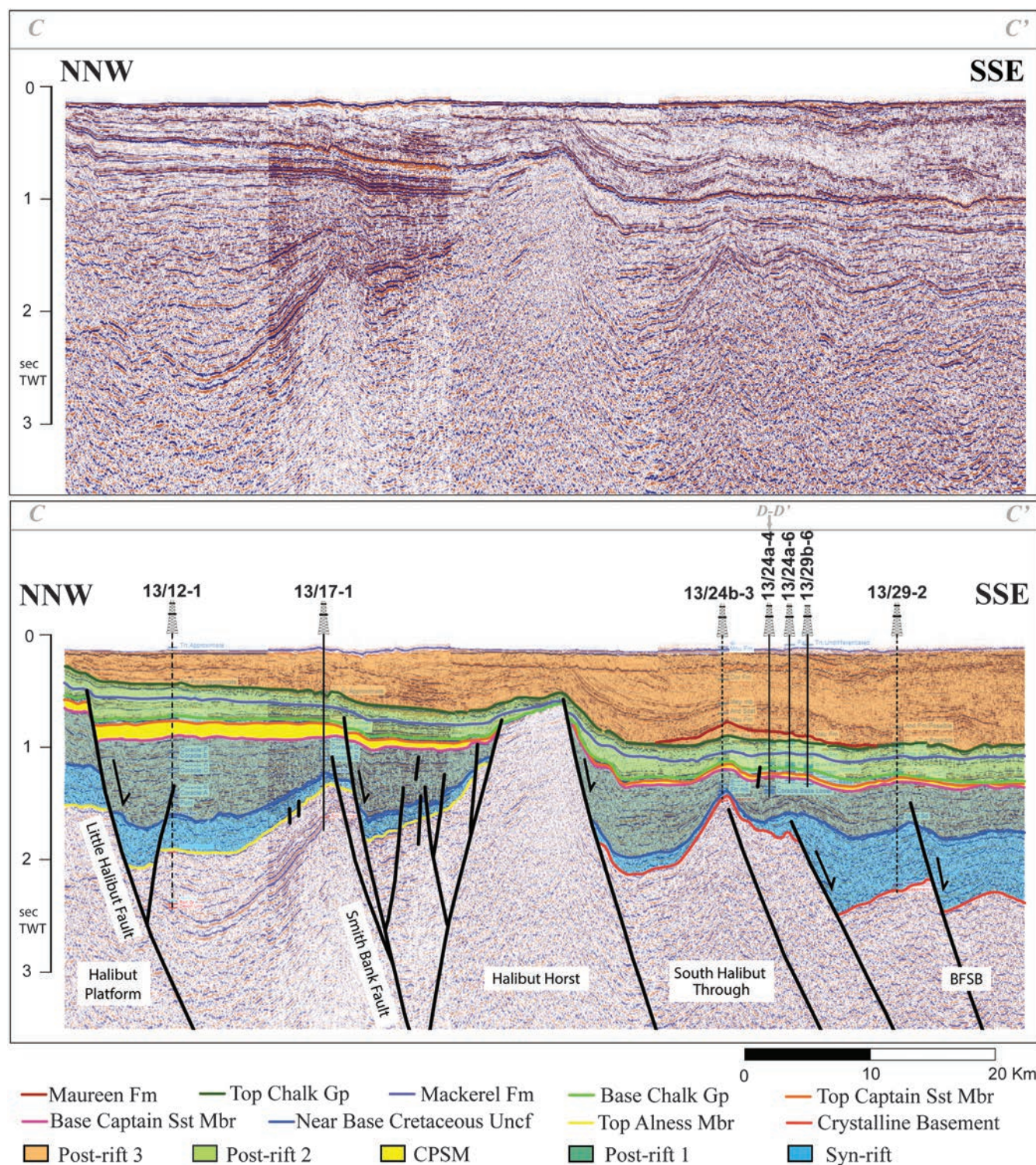


**Figure 7.** Central north-northwest/south-southeast-striking well-log correlation panel corresponding to the seismic line used in Figure 6 highlighting the effect that syn- and post-depositional faulting had on the thickness distribution of the Cromer Knoll Group in general and Captain Sandstone Member in particular.



hydrocarbon play fairway that displays no evidence of compartmentalization (Wilson et al., 2005). Reservoir characteristics such as high net-to-gross, high-porosity, high-permeability, extensive lateral continuity, and aquifer support (Pincock and Clitheroe, 1997; Rose, 1999; Du et al., 2000; Rose et al., 2000; Hampson et al., 2010), all suggest that high injectivity would be possible and overpressuring unlikely to occur.

fer support (Pincock and Clitheroe, 1997; Rose, 1999; Du et al., 2000; Rose et al., 2000; Hampson et al., 2010), all suggest that high injectivity would be possible and overpressuring unlikely to occur.



**Figure 8.** Easternmost north-northwest/south-southeast-striking seismic line (C-C') across the Halibut Platform, Halibut Horst (Captain Ridge), the South Halibut Basin, and Banff Subbasin. Part of the seismic section runs along the western boundary of the Blake Field. Major fault displacement and stratal growth within the Cromer Knoll Group is shown in the section, in particular against the south Halibut Horst bounding fault (Banff Subbasin [BFSB]).



## Data and methods

The seismic database available to this study consisted of eight time-migrated 3D volumes and a tight grid of 2D seismic lines (Figure 3) that extends over a combined area of 9500 km<sup>2</sup>. Particular use was made of four overlapping 3D seismic data volumes covering approximately 5000 km<sup>2</sup>. Although centered on the Captain Field, the 3D seismic data extend over most of the basin area. Given its areal coverage, line spacing of 12.5 m and well control, the eight 3D seismic data sets give an unprecedented control on subsurface mapping. Crucially, the new interpretations extend the mapping to more westerly areas than in previous studies.

Calibration of the seismic interpretation was provided by access to more than 100 exploration wells, all of which have been integrated into the study, with additional data from appraisal and development wells drilled on the producing fields (Figure 3). The density of well data permits accurate mapping of individual horizons and affords excellent control on velocities by which to constrain the depth conversion.

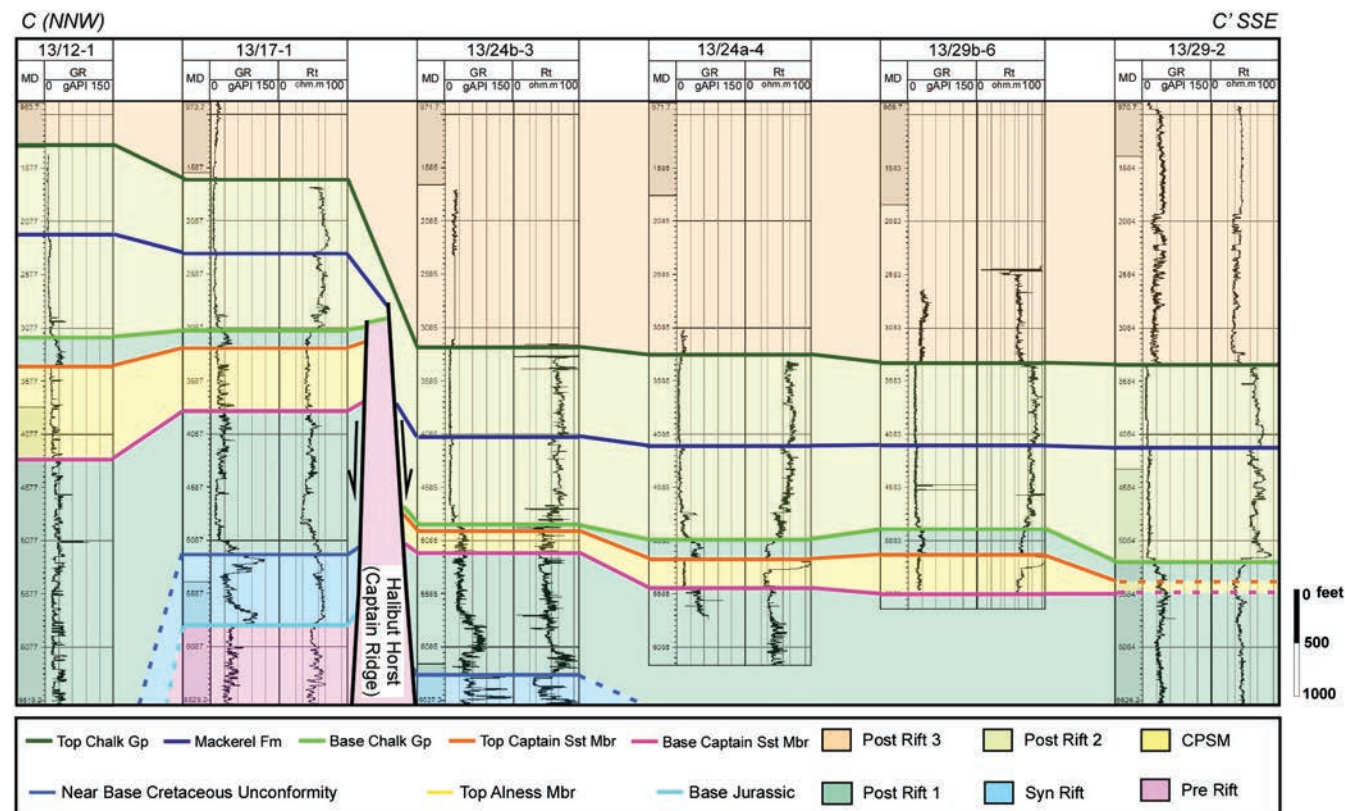
## Results

### Seismic interpretation

Despite the comprehensive seismic database and excellent borehole calibration, seismic recognition of the Captain Sandstone Member has generally proved to be

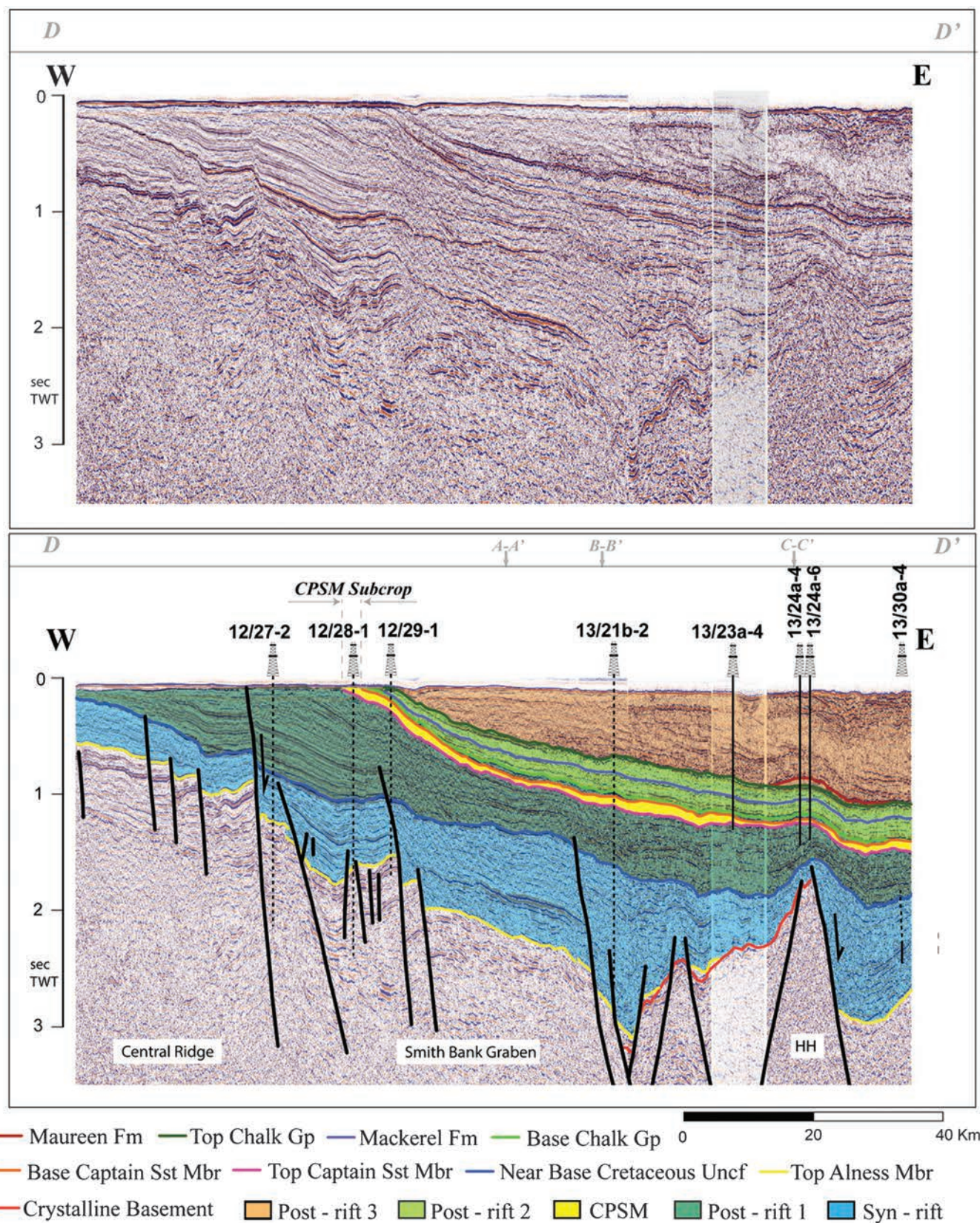
difficult in eastern areas largely because of the deleterious effect on imaging caused by its Chalk Group cover (Argent et al., 2002), the lack of a clear acoustic impedance contrast between the sandstone and its encasing shale (Wilson et al., 2005), and to tuning effects from local thinning of the Captain Sandstone Member over persistent intrabasinal paleohighs. Where both the Chalk Group cover is present and tuning effects are prominent, seismic interpretation of the Top Captain Sandstone Member horizon has been carried out by using the Base Hydra Formation horizon (Base Chalk Group) as a proxy for the underlying Captain Sandstone horizon, with the Base Hydra Fm being downshifted by 10 ms. This interpretation was made by the identification of a prominent and laterally extensive (early Albian; K50) maximum flooding event within the overlying Rødby Formation seal. Mapping of the base Captain Sandstone Member is based on the recognition of the (earliest late Aptian, K45) basal sequence boundary below the Captain Sandstone Member (Copestake et al., 2003; Wilson et al., 2005). The thin and locally discontinuous nature of the Mid Captain Shale (Jin et al., 2012) does not allow it to be identified throughout the play fairway, and it can only be confidently mapped on seismic in more northerly areas, such as in the Wick subbasin.

In the western area of the MF Basin, where the Captain Sandstone Member comes up to subcrop the seabed, the



**Figure 9.** Easternmost north-northwest/south-southeast-striking well-log correlation panel corresponding to the seismic line used in Figure 8 highlighting the effect that syn- and postdepositional faulting had on the thickness distribution of the Cromer Knoll Group in general and the Captain Sandstone Member in particular.





**Figure 10.** West-east-striking regional seismic line (D-D') constructed along the axis of the Central Ridge, Smith Bank Graben, and South Halibut Basin hanging-wall depocenter. The line shows the pronounced easterly dip imparted on the basin as a result of Cenozoic uplift. The effect of the basin tilt is such that the Captain Sandstone Member rises to subcrop the seabed in the highlighted area, which corresponds to UKCS quadrant 12. The line emphasizes the Cromer Knoll Group's easterly tapering prograding (clinoform) geometry (Halibut Horst [HH]).



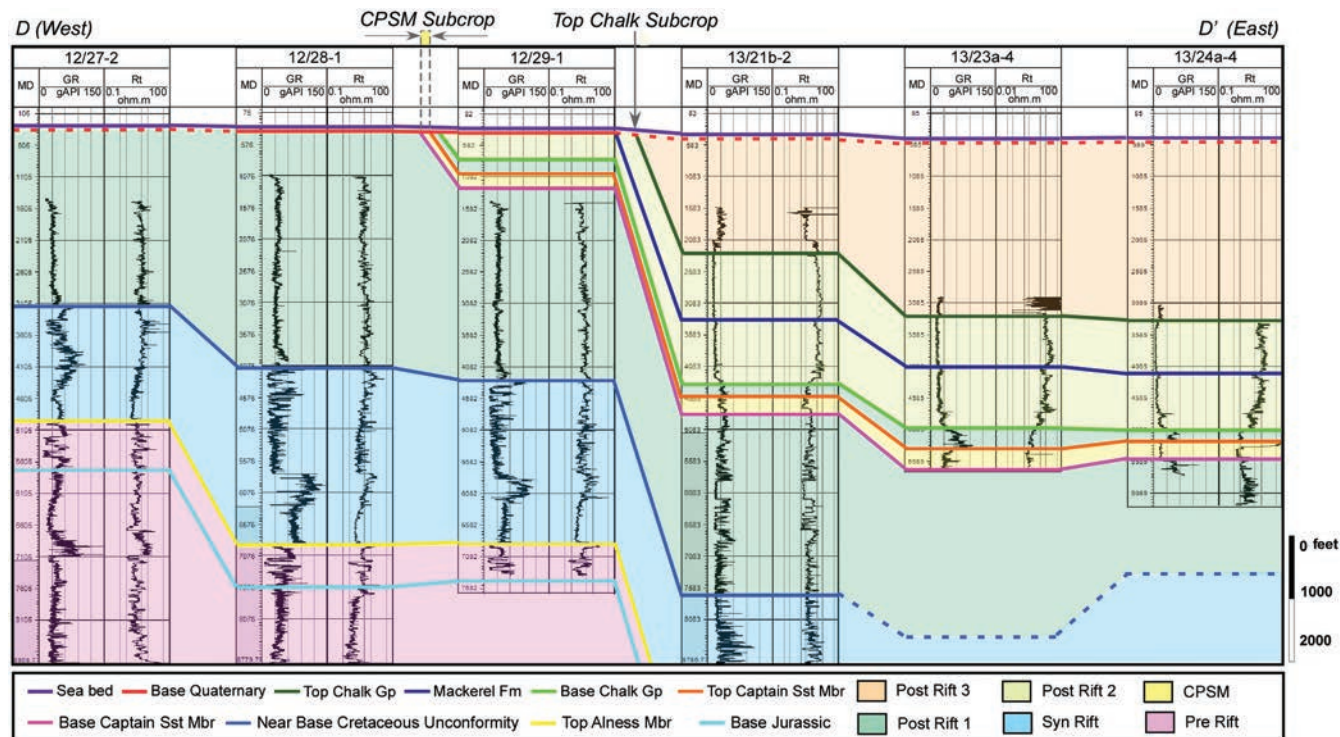
absence of the Chalk Group in the overburden leads to a considerable improvement in the fidelity of the seismic data and the top of the aquifer and its subcrop pattern may be interpreted and mapped with better confidence (Argent et al., 2002). However, partial obscuring of shallow reflections due to seabed multiples remains problematic over most of the study area. It is important to note that the seismic mapping of the Captain Sandstone Member interval (the base and top marker) relies on the chronostratigraphical principle of reflector continuity and is not solely based on present lithofacies (e.g., muddy facies south of the Bosies Bank Fault; Figure 1).

The main structural and stratigraphic character of the greater Captain area is well-illustrated by the use of three north-northwest/south-southeast-striking dip lines, one west-east-striking line running along the basin axis, and four well-correlation panels corresponding to each seismic transect (Figures 4, 5, 6, 7, 8, 9, 10, and 11). The north-northwest/south-southeast lines demonstrate that the area is dominated by a series of west-east to west-southwest/east-northeast-striking normal faults. Observations of thickness and facies variations in the study area, in addition to those of the eastern Buzzard Field (Ray et al., 2010) (Figure 3), demonstrate that the main phase of the extensional activity was during the Upper Jurassic (synrift) interval.

The thickest Early Cretaceous sequences occur above all the identifiable synrift subs basin depocenters but most notably in the Wick subs basin, which is situated

on the south side of the basin-bounding Wick Fault. Similar thick Lower Cretaceous packages are also found in the Smith Bank Graben and South Halibut Basin. Despite sedimentation patterns being generally consistent with deposition during a phase of gentle (postrift) thermal subsidence, thinning of the Cromer Knoll Group is noted over intrabasin highs. This appears to be a result of a combination of onlap and erosional truncation of the lower intraformational sequences against crestal regions, which attests to foot-wall areas being structurally elevated and marked by condensed sequences, either as a consequence of continued extension or simply by virtue of being persistent (submarine) highs. A well correlation panel (Figure 9) corresponding to the seismic line C-C' (Figure 8) shows that, although the component parts of the Captain Sandstone Member exhibit up-dip thinning and pinch-out. There is also evidence for progressive overstep of the unit with time, suggesting that sedimentation patterns reflect progressive drowning of the basin in response to thermal subsidence.

It is clear from the seismic interpretation that many of the major Upper Jurassic (synrift) faults were reactivated because they offset younger stratal packages. They also display an increased net fault throw toward western parts of the basin. Such systematic variations in displacement occur along the length of the fault systems. In many instances, the largest faults offset the Captain Sandstone Member and the Base Tertiary (Top



**Figure 11.** West-east striking well-log correlation panel corresponding to the seismic line used in Figure 10 showing the distribution of the Captain Sandstone Member along the depositional axis of the reservoir play fairway. The reservoir is effectively a continuous system between its seabed subcrop in quadrant 12 to where the upper unit shales out in UKCS quadrant 15, a distance of more than 150 km.

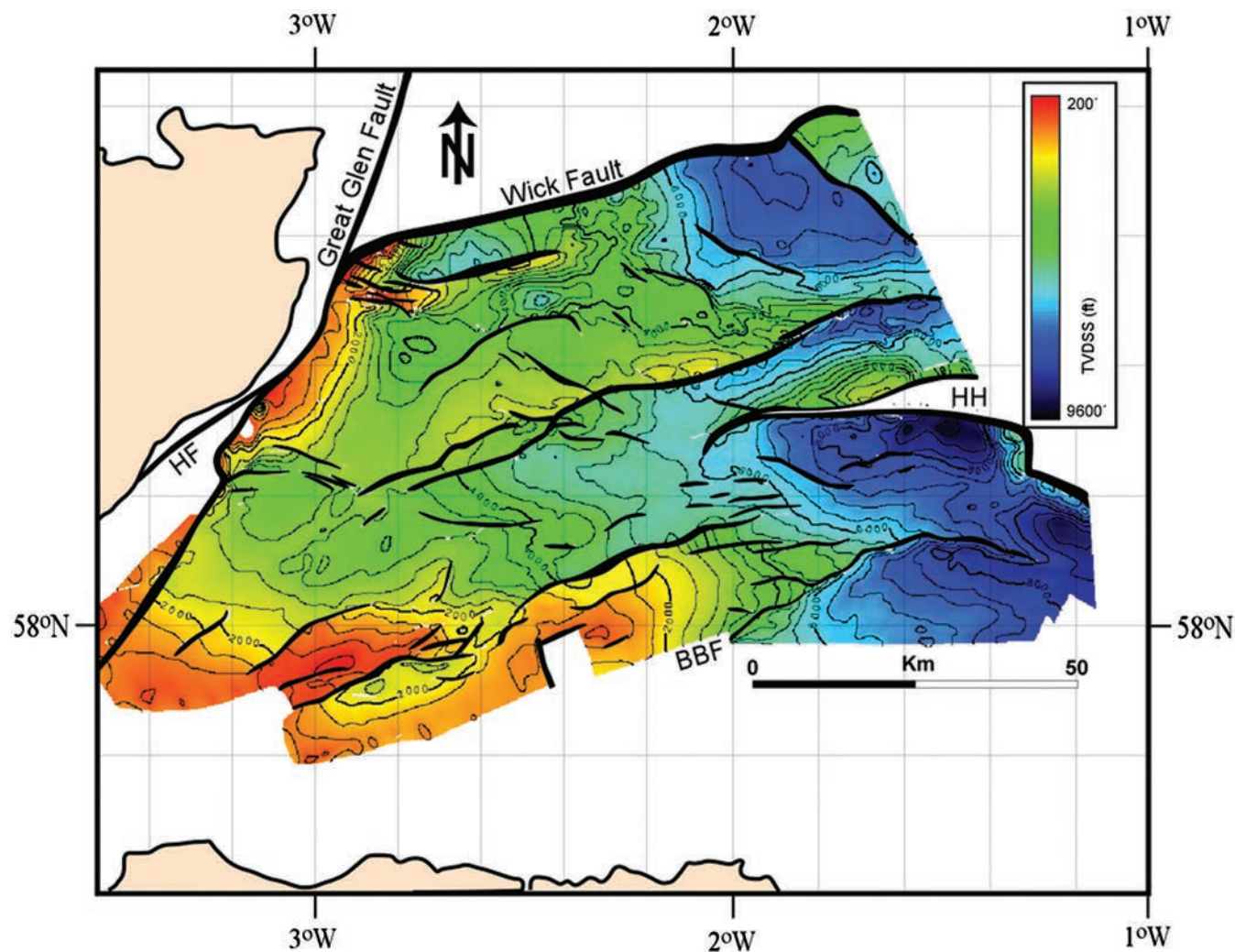
Chalk Group) reflector. Several faults propagate up to tip out in the Paleogene section or rise to seabed in areas where the Early Cenozoic or older strata subcrop the seabed. Examples of this phenomenon occur along strike from the Captain Field on faults such as the Smith Bank Fault and along the basin-bounding Wick Fault to the north (Figures 4 and 6).

Offset of the Top and Base Chalk Group reflectors along the northern and southern Smith Bank High bounding faults (including the Smith Bank Fault), the upward termination of fault tips in the Paleogene section (Figures 4 and 6), and a relatively uniform thickness distribution of the Chalk Group combine to suggest that fault reactivation occurred in the Late Paleocene-Early Eocene (approximately 55 million years ago), implying a genetic link to Atlantic Margin deformation (Argent et al., 2002). Notable fault displacement also affects the Base Chalk Group reflector in the Halibut Horst, east of seismic line C-C' (Figure 8), further confirming post-Cretaceous offset of Paleogene strata.

In contrast to the north-northwest/south-southeast sections, the construction of a west-east-striking, well-

tied arbitrary seismic line, and a well-correlation panel through the Blake Field in the South Halibut Basin, demonstrate the lateral continuity of the Captain Sandstone Member along the axis of the basin (Figures 10 and 11). Toward the west, an easterly dip of between 2° and 4° is apparent. As a result, the Top Mackerel Formation (intraChalk Group) and Top Cromer Knoll Group horizons rise to subcrop the seafloor between wells 12/29-1 and 12/28-1. The highest continuous reflector that remains buried across the study area is the Near Base Cretaceous Unconformity (BCU), meaning that only older horizons can be mapped throughout the whole seismic data set (Figure 12).

The overall geometry of the Cromer Knoll Group is that of an eastward-tapering prograding sedimentary wedge, with internal geometries consistent with low-angle, easterly downlapping, (shingled) clinoforms (Figures 10 and 11). Western parts of the wedge contain the Captain Sandstone Member, and are erosionally truncated at seabed and overlain by a thin (approximately 20 m) Quaternary cover containing subglacial channel networks (Andrews et al., 1990; Stoker et al., 2011).



**Figure 12.** Top depth structure map of the top synrift (Near BCU; Halibut Horst [HH] and Bosies Bank Fault [BBF]).



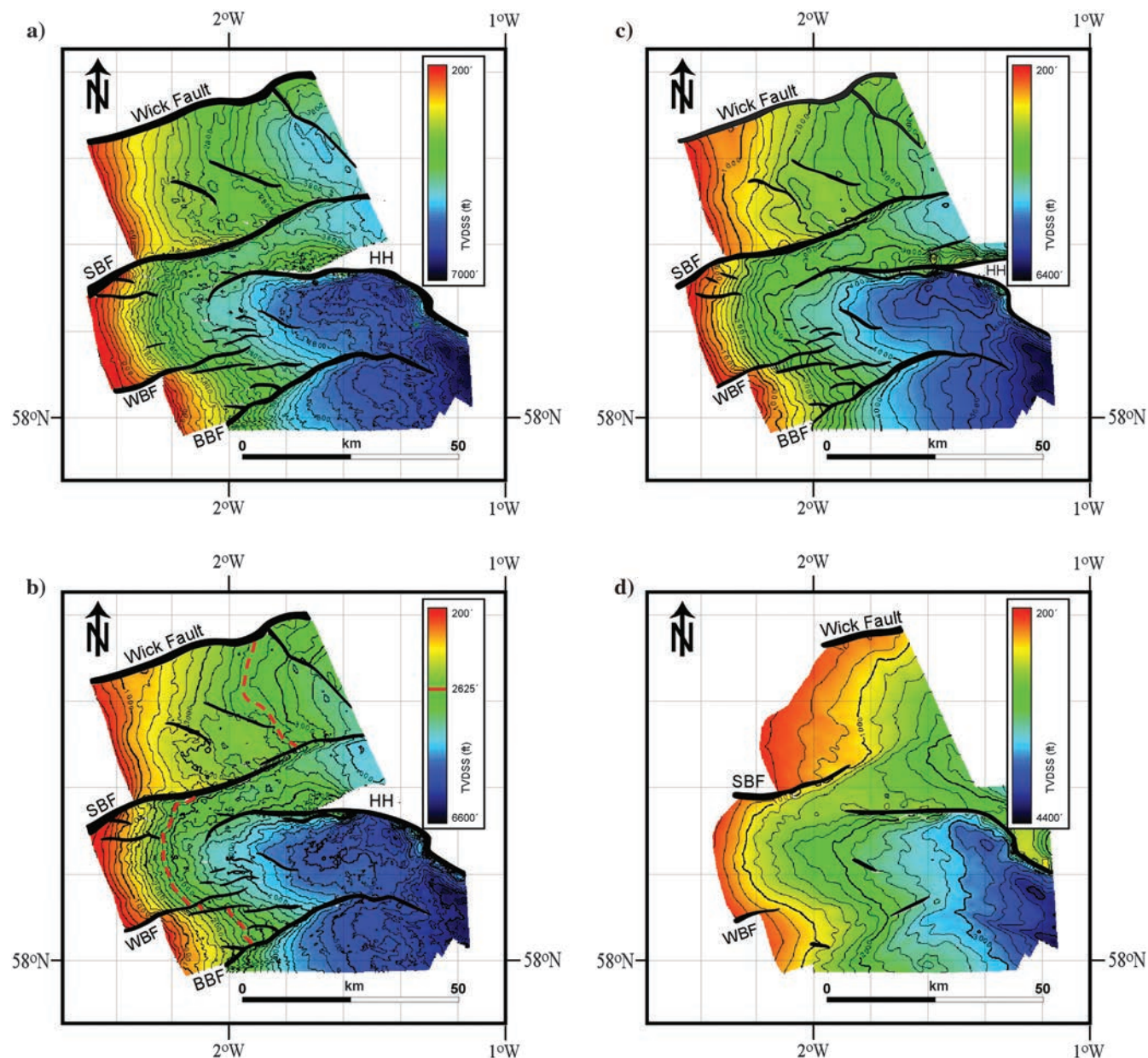
Well correlations in the area where the clinoforms are thickest confirm that the Captain Sandstone Member remains dominated by good reservoir properties until its subcrop between the location of the 12/29-1 and 12/28-1 wells (Figures 10 and 11).

### Depth conversion

Seismic mapping was initially undertaken on time sections, and the resultant maps were depth converted to produce top structure (Figures 12 and 13) and iso-chore maps (Figure 14) for each of the main horizons and the key stratigraphic intervals that they define. All final maps were cross checked against well data and

corrections were applied using a residual trend that minimized the difference between the predicted true vertical depth subsea (TVDSS) and the actual depth of each marker for each particular wellbore.

Based on the number of well penetrations and the areal extent of each particular horizon, the depth conversion was performed using a layer-cake model with accurate interval velocities derived from up to 75 individual velocity surveys from wells in the area. Various interpolation algorithms were tested, and a minimum curvature algorithm was found to best reflect the residual areal distribution. Care was taken to ensure that the residuals were minimized on a well-to-well basis, with a deviation



**Figure 13.** Top depth structure maps in feet of the (a) Base Captain Sandstone Member; (b) Top Captain Sandstone Member with the 800 m (2625 ft) contour as a dashed red line, indicating the depth threshold needed to maintain CO<sub>2</sub> in the supercritical phase; (c) base Chalk Group; and (d) top Chalk Group. The imaged area coincides with the dashed-box area shown in Figure 12 (Bosies Bank Fault [BBF], Halibut Horst [HH], Smith Bank Fault [SBF], and West Bank Fault [WBF]).

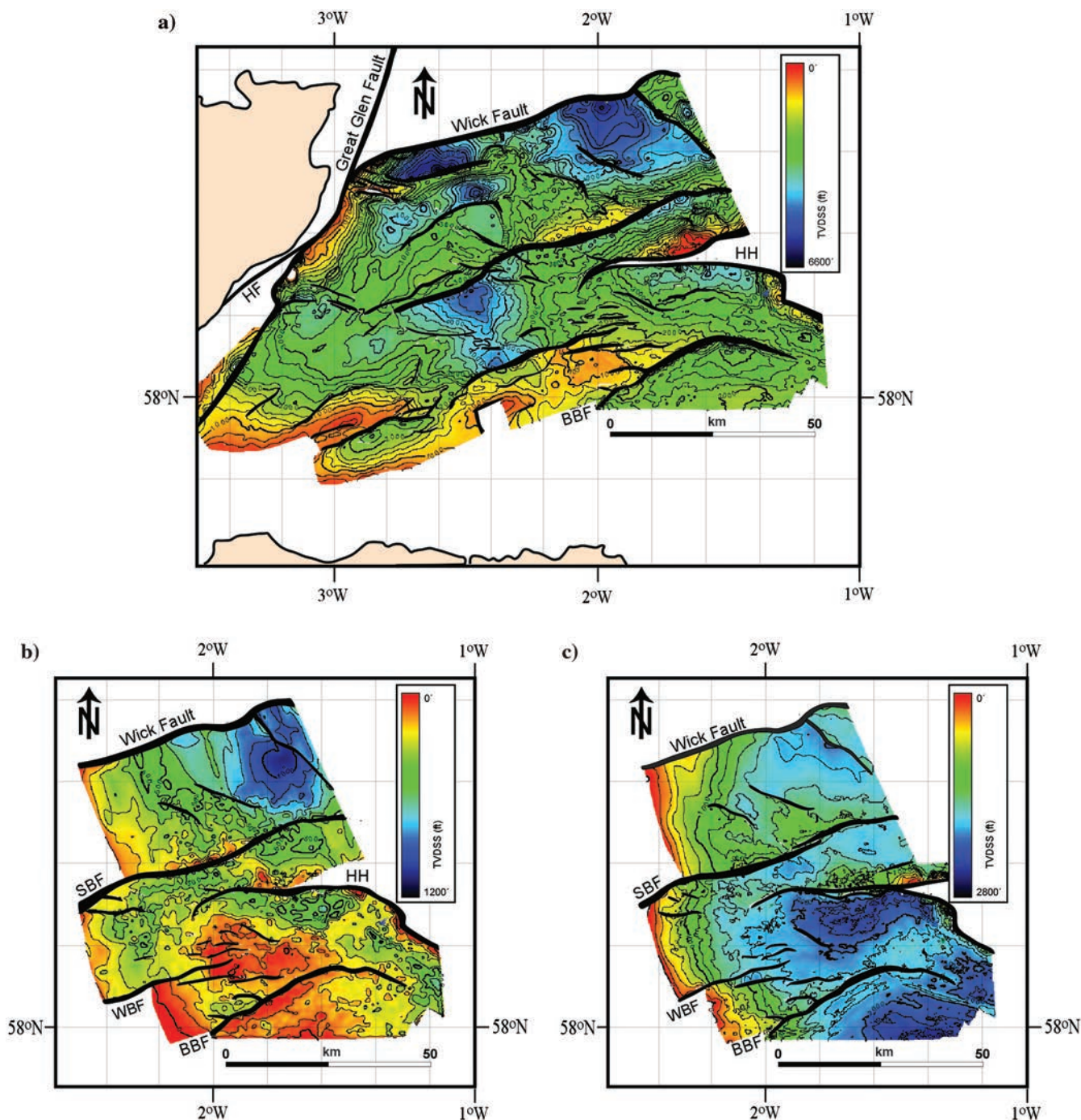
generally in the range 1%–3% of their actual TVDSS values. Particular emphasis was given to the top Captain Sandstone Member depth structural map because its form and subcrop are critical elements used to assess its capacity to sequester CO<sub>2</sub> in the Captain Sandstone Member aquifer.

Our high-resolution mapping allows us to produce a subcrop map for the Inner MF. The map shows the subcrops for the tilted and truncated Cretaceous and Cenozoic lithostratigraphic units in general and for

the Captain Sandstone Member in particular (Figure 15), which also highlights the distribution and nature of all of the (reactivated) faults that propagate up to the seabed, especially those in the western part of the basin, where the risk of CO<sub>2</sub> leakage from the saline aquifer is greatest.

### Implications for CO<sub>2</sub> storage

Due to the density contrast between dry CO<sub>2</sub> and the formation brines, supercritical and gaseous-phase CO<sub>2</sub>



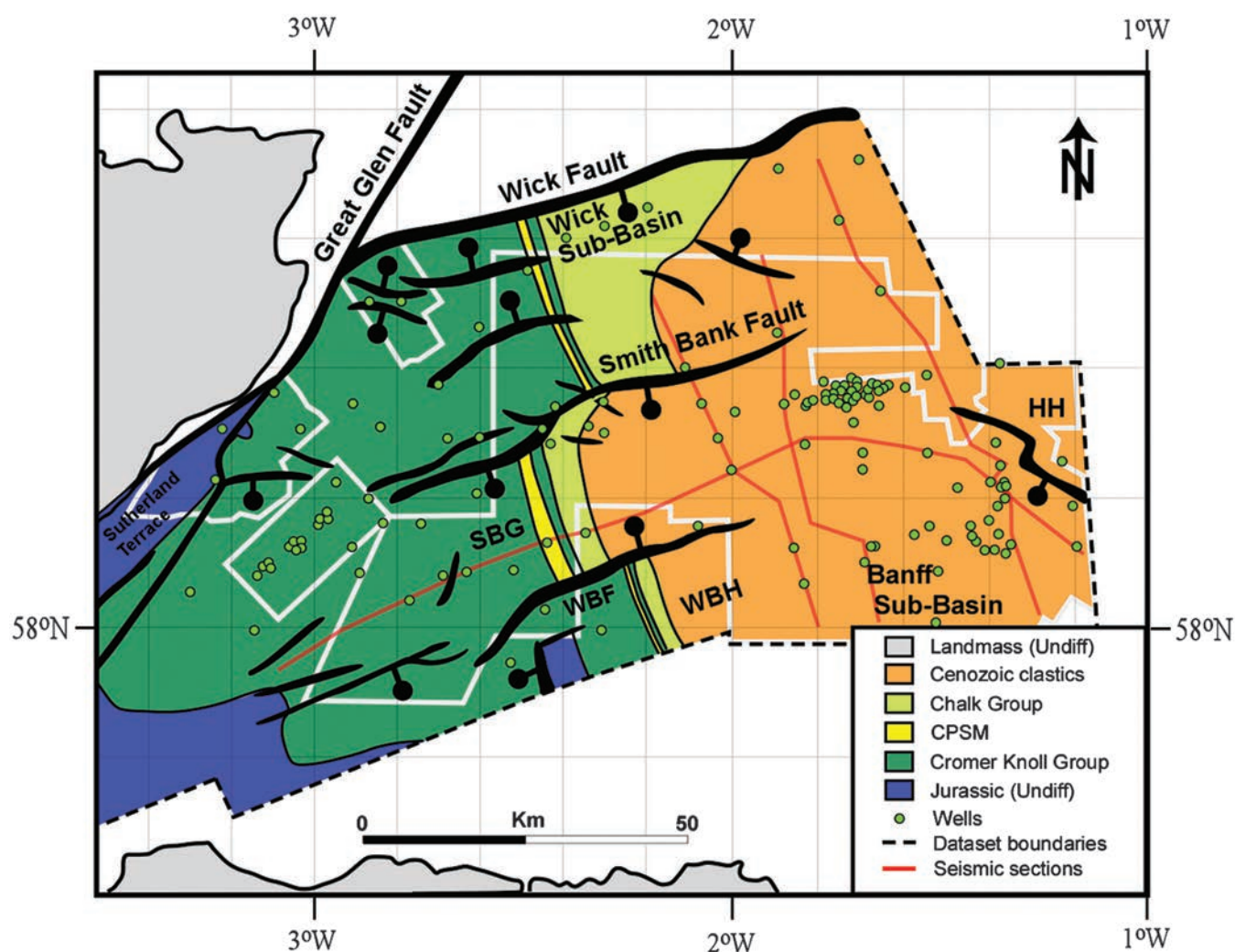
**Figure 14.** Isochore maps in feet for the (a) Cromer Knoll Group; (b) Captain Sandstone Member; and (c) Chalk Group (Bosies Bank Fault [BBF], Halibut Horst [HH], Smith Bank Fault [SBF], and West Bank Fault [WBF]).



retain their buoyancy in the subsurface. Thus, injection of CO<sub>2</sub> in either form into a structural closure or saline aquifer requires an effective seal (caprock) to guarantee safe, long-term containment. The occurrence of hydrocarbons in Captain Sandstone Member reservoirs of the Atlantic, Blake, Captain and Cromarty Fields demonstrates that the Carrack and Rødby Formations can entrap long-chained inert hydrocarbon molecules. However, in the absence of any evidence for significant volumes having been encountered in the basin, it remains uncertain whether those formations can retain the smaller and nimble CO<sub>2</sub> molecule. In the case of the calcareous and smectitic mudstones of the Rødby Formation seal, it is important to ensure that the injected CO<sub>2</sub> will not react aggressively with it and thus weaken its sealing potential (Gunter et al., 2004; Rochelle et al., 2004).

Presuming that the physiochemical integrity of its seal is maintained, the easterly tilt and pressure of the

Captain Sandstone Member saline aquifer would be the key issue because any CO<sub>2</sub> that would be injected could migrate through the homogeneous, open aquifer toward its subcrop or outcrop (Gunter et al., 2004; Takasawa et al., 2010; Thibeau and Mucha, 2011; Kampman et al., 2014). As the geologic mapping demonstrates, the Captain Sandstone Member lacks any substantial structural closure along the migration pathway to retain CO<sub>2</sub>. Residual, solubility, or mineral trapping are therefore the only mechanisms that could aid containment over a sufficiently long time interval to permit a substantial fraction of the injected mass to be sequestered. In the case of mineral trapping, the formation of new mineral assemblages are slow processes that can span up to tens of thousands of years and are controlled by the mineralogy and fluid properties of the host rock and the local and regional thermodynamic conditions, variables that are hard to accurately quantify and difficult to constrain via modeling for the particular thermodynamic



**Figure 15.** Subcrop map for the Inner Moray Firth Basin derived from the seismic interpretation. The map differs from previously published subcrop patterns and highlights the important role that Cenozoic fault reactivation and regional uplift play in controlling the distribution of Mesozoic and Cenozoic sequences. This map provides a newfound basis to investigate paleoseepages from the Captain Member stratigraphy, aiding in the evaluation of CO<sub>2</sub> monitoring site locations if injection takes place in the basin (Bosies Bank Fault [BBF], Halibut Horst [HH], Smith Bank Graben [SBG], West Bank Fault [WBF], and West Bank High [WBH]).

conditions of the aquifer (Gunter et al., 2004; Rochelle et al., 2004; Xu et al., 2004; Pickup et al., 2011; Bickle et al., 2013; Kampman et al., 2014). Consequently, it is possible that solubility and residual trapping on their own might not prove sufficient to counteract CO<sub>2</sub> migration toward the subcrop on the time scales needed to prevent gas escape. CO<sub>2</sub> injection into the Captain Sandstone Member aquifer consequently carries a degree of risk and the uncertainty of leakage at the subcrop at present.

Lewicky et al. (2006) compile an extensive list of naturally occurring and industrially derived CO<sub>2</sub> accumulations that have undergone leakage from storage reservoirs in recent times. The authors found that 75% of all naturally occurring leakage occurred as a consequence of faulting and fracture of the sealing caprock, whereas the remaining 25% were undetermined but could potentially also be attributed to faulting. Leakage of deep-sourced, supercritical CO<sub>2</sub> along extensional faults is well-documented in the Paradox Basin in Utah (Shipton et al., 2004; Dockrill and Shipton, 2010; Bickle et al., 2013; Kampman et al., 2013) and Italy (Chiodini et al., 2004; Minissale, 2004; Colletini et al., 2008). In these examples, subsurface degassing and surficial leakage results from the combined effect of horizontal, up-dip migration, and vertical migration along nonsealing fault planes to the surface. These observed phenomena confirm the effectiveness of faults to serve as migration conduits for supercritical and gaseous-phase CO<sub>2</sub> and are a risk to safe storage. As Williams et al. (2016) demonstrate, some segments of the regional faults are likely to be near-critically stressed under some of the possible stress conditions and therefore would not require a considerable pore-pressure increase to become reactivated.

Given the widespread faulting affecting the Captain Sandstone Member aquifer and its overburden, a thorough assessment of the sealing capacity of these faults is critical if injection is to take place. In particular, those faults that reach the seabed are to be considered of high leakage risk (Figure 15). Even faults that do not fully propagate to the seabed and tip out within the buried Paleogene section may provide potential leakage conduits to clastic reservoirs that they intersect either as they stand or due to the elevated pore pressures that are likely to result from large-scale fluid injection (Williams et al., 2016).

Additional evidence of recent fluid migration and escape toward the eastern region of the MF Basin occurs in the form of pipes and pockmarks because it attests to gas escape having affected the basin (e.g., Andrews et al., 1990; Judd et al., 1994), and their occurrence adds another level of risk and uncertainty to storage options.

The results of our mapping of the Captain Sandstone Member thus serve to demonstrate that great care needs to be taken in the geologic assessment of saline aquifers. Although it is important to stress that our results do not impact the storage potential at other North

Sea sites, they do indicate that the Captain Sandstone Member is not the best one to use as an exemplar.

## Conclusion

Use of an extensive seismic and well database from the MF Basin in the North Sea affords the opportunity to critically assess the storage and sealing capacity of Lower Cretaceous Captain Sandstone Member, a sedimentary aquifer, which has been previously considered to represent a good candidate for CO<sub>2</sub> injection and long-term storage. Although our geologic studies do not completely invalidate use of the Captain Sandstone Member aquifer as a carbon storage site, the lack of CO<sub>2</sub> does imply that containment and sealing capability remains unproven in extant traps along its reservoir play fairway.

Our regional mapping shows that the Captain Sandstone Member saline aquifer is continuous and largely uncompartmentalized. As such, it is a highly efficient, open, and largely homogeneous reservoir system to its seabed subcrop in the west. As such, it has the potential to allow unhindered up-dip migration of gaseous CO<sub>2</sub>, to displace and expel brine all the way to the seabed subcrop and along any (reactivated) open faults that tip out within the Early Cenozoic (Paleogene) clastic section. Because CO<sub>2</sub> storage in regional saline aquifers remains largely conceptual and uncertainties exist concerning the long-term behavior and containment of CO<sub>2</sub>, our new results imply that use of the Captain Sandstone Member saline aquifer for carbon storage is premature.

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the merits of using the Captain Sandstone Member saline aquifer as an appropriate CO<sub>2</sub> repository in particular. We thank J. Hernandez for his valuable time and input provided for the depth conversion and R. Jamieson for her insightful reviews and suggestions.

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